Karlsruhe Institute of Technology

Improved modelling of charge trapping and impact ionization in phonon-based crystal detectors used for dark matter searches

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IDM 2024 - Karlsruher Institut für Technologie

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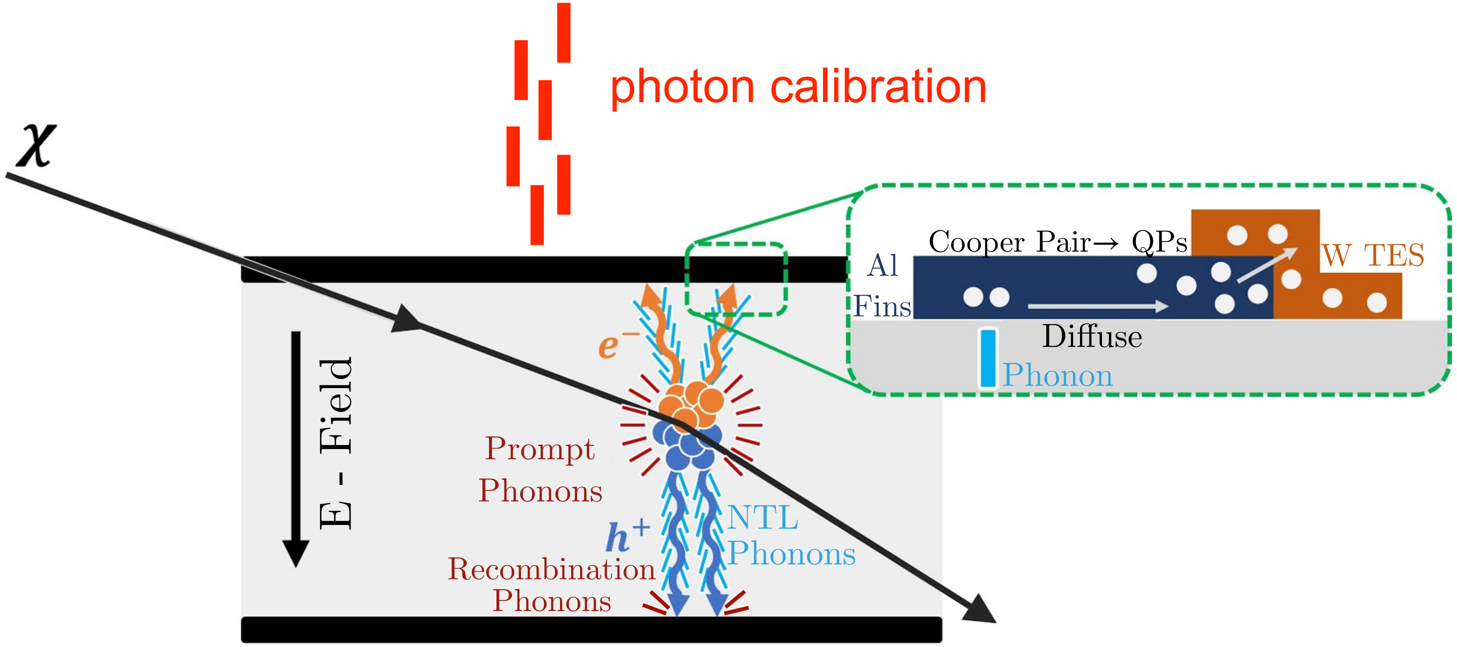
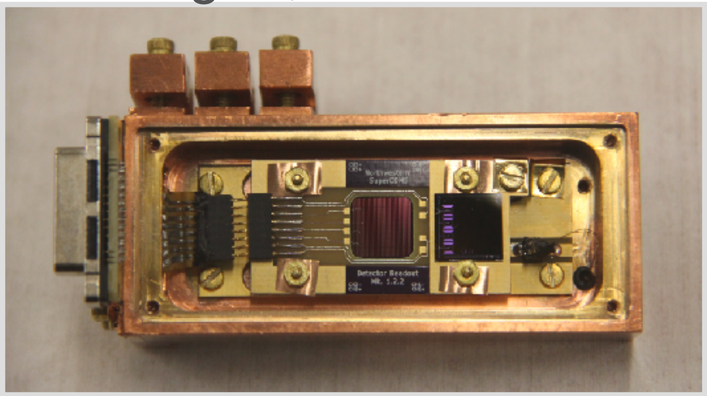
Phonon-based crystal detectors

SuperCDMS High-voltage eV-scale (HVeV)



~1g Si, 100 V bias

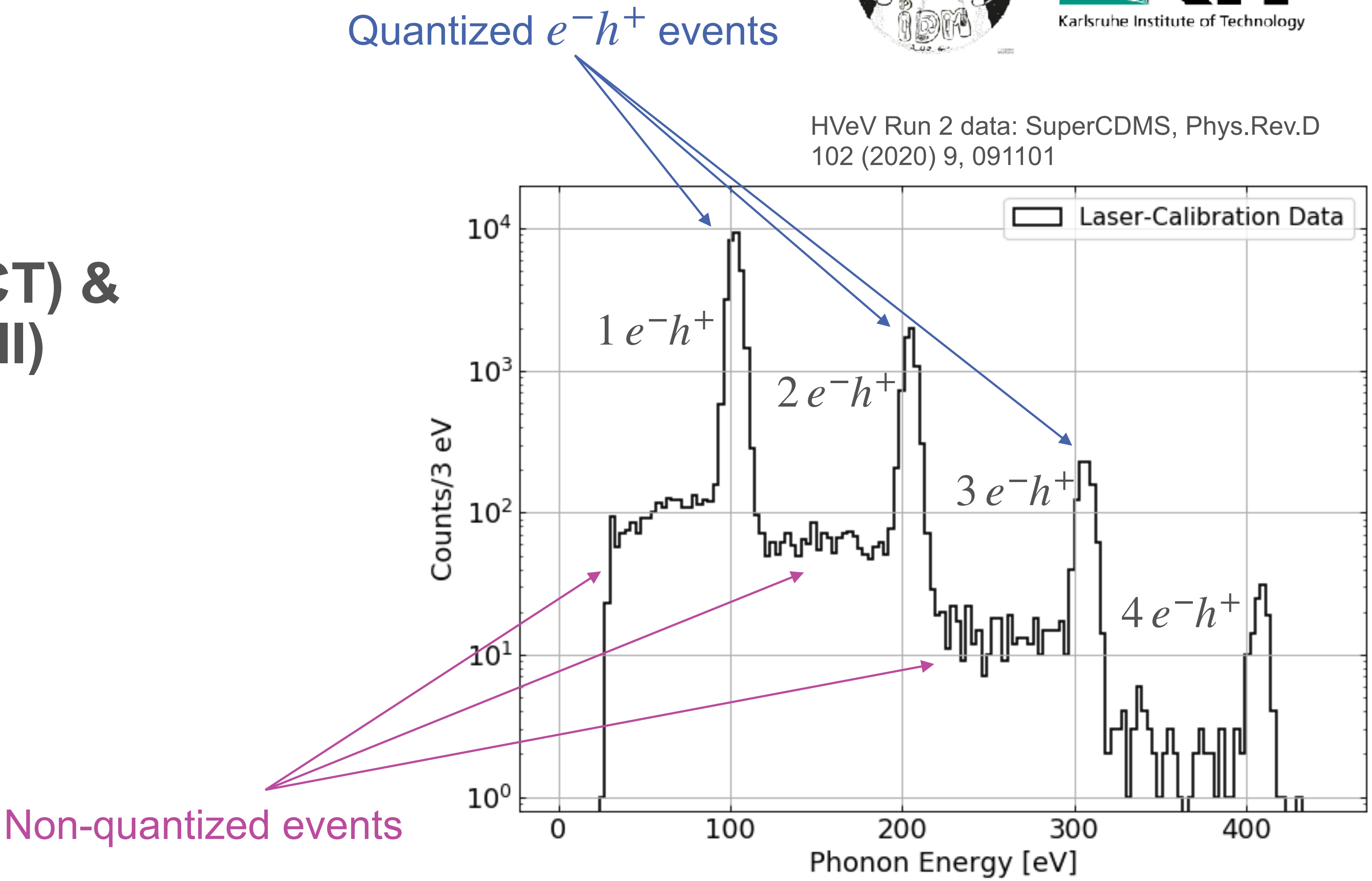


$$E_{\text{phonon}} = E_{\text{recoil}} + \boxed{n_{eh} \cdot e \cdot V_{\text{bias}}}$$

Neganov-Trofimov-Luke gain

Detector response

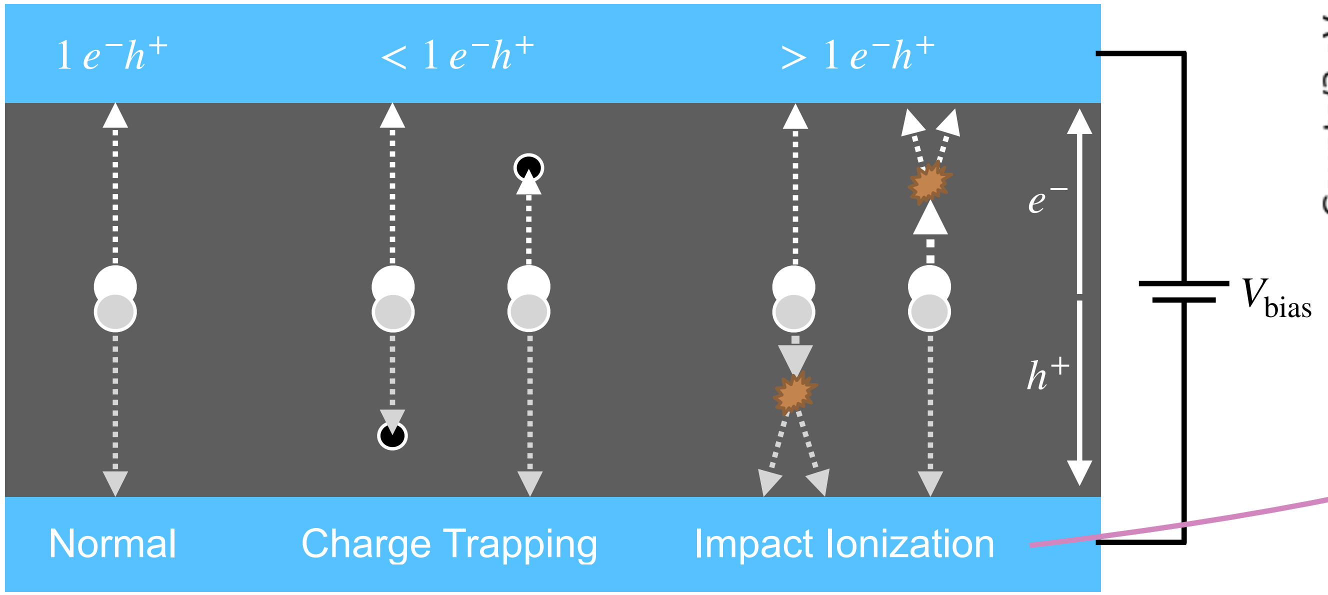
- Resolution
- Ionization Yield
- **Charge trapping (CT) & Impact Ionization (II)**
- **Other effects**

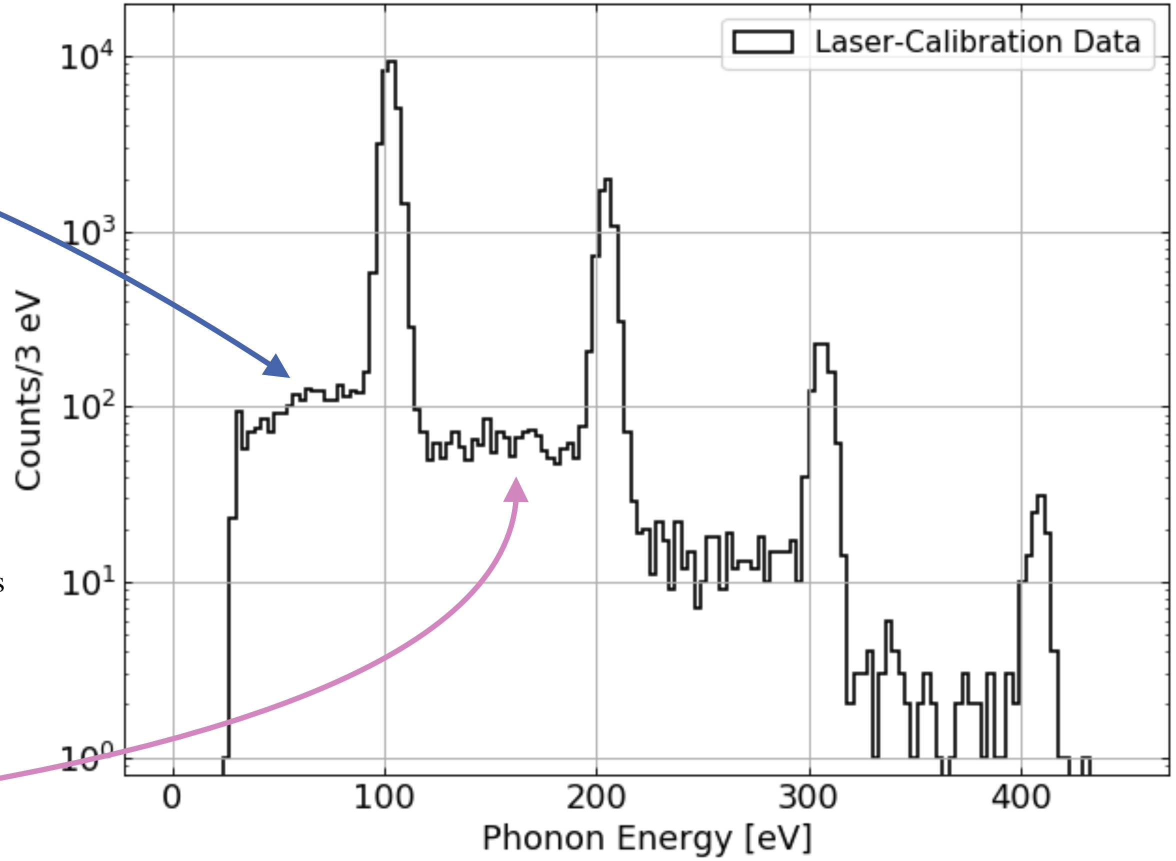


Detector response

- **Charge trapping (CT) & Impact Ionization (II)**

HVeV Run 2 data: SuperCDMS, Phys.Rev.D 102 (2020) 9, 091101





“Exponential” CTII model

1. e^- and h^+ propagate along z-direction parallel to electric field.
2. Parameterize CT/II probabilities by characteristic lengths τ_i
3. Find analytical solutions for each unique process and various event types

$$\tau_{\mathrm{CT},e} = \frac{-1}{\ln(1 - f_{\mathrm{CT},e})} \qquad \tau_{\mathrm{CT},h} = \frac{-1}{\ln(1 - f_{\mathrm{CT},h})}$$

$$\tau_{\mathrm{II},ee} = \frac{-1}{\ln(1 - f_{\mathrm{II},ee})} \qquad \tau_{\mathrm{II},he} = \frac{-1}{\ln(1 - f_{\mathrm{II},he})}$$

$$\tau_{\mathrm{II},eh} = \frac{-1}{\ln(1 - f_{\mathrm{II},eh})} \qquad \tau_{\mathrm{II},hh} = \frac{-1}{\ln(1 - f_{\mathrm{II},hh})}$$

$$P_i(z) = \frac{1}{\tau_i} e^{-z/\tau_i}$$

“Exponential” CTII model

1. e^- and h^+ propagate along z-direction parallel to electric field.
2. Parameterize CT/II probabilities by characteristic lengths τ_i
3. Find analytical solutions for each unique process and various event types

$$P_1(E) = \begin{cases} \frac{1}{\tau_{\mathrm{CTs}}} e^{-T_{\mathrm{s}} \cdot E} & 0 \leq E < 1 \\ 0 & \text{else} \end{cases}$$

$$P_{26}(E \,|\, T_{\mathrm{s}} \neq T_{\mathrm{o}}) = \begin{cases} \frac{e^{-\frac{23T_{\mathrm{o}}E}{4} - T_{\mathrm{s}}E}(\zeta_1(E)+\zeta_2(E)+\zeta_3(E))}{4T_{\mathrm{o}}\tau_{\mathrm{IIoo}}(T_{\mathrm{o}}-T_{\mathrm{s}})^2 T_{\mathrm{s}}^2 (3T_{\mathrm{o}}+T_{\mathrm{s}})\tau_{\mathrm{IIso}}^2} & 1 \leq E < 2 \\ \frac{e^{-\frac{7}{2}T_{\mathrm{o}}(1+3E) - T_{\mathrm{s}}(5+6E)}(\eta_1(E)+\eta_2(E)+\eta_3(E)+\eta_4(E)+\eta_5(E)+\eta_6(E))}{4T_{\mathrm{o}}\tau_{\mathrm{IIoo}}(T_{\mathrm{o}}-T_{\mathrm{s}})^2 T_{\mathrm{s}}^2 (T_{\mathrm{o}}+T_{\mathrm{s}})(3T_{\mathrm{o}}+T_{\mathrm{s}})\tau_{\mathrm{IIso}}^2} & 2 \leq E < 3 \\ \frac{e^{-2T_{\mathrm{s}}(-1+E)}(\psi_1(E)+\psi_2(E))}{4T_{\mathrm{o}}\tau_{\mathrm{IIoo}} T_{\mathrm{s}}^2 (T_{\mathrm{o}}+T_{\mathrm{s}})(3T_{\mathrm{o}}+T_{\mathrm{s}})\tau_{\mathrm{IIso}}^2} & 3 \leq E < 4 \\ 0 & \text{else,} \end{cases}$$

where

$$\zeta_1(E) = -9e^{\frac{1}{12}(69T_{\mathrm{o}}E+T_{\mathrm{s}}(4+8E))}T_{\mathrm{o}}(T_{\mathrm{o}}-T_{\mathrm{s}})^2 + 16e^{\frac{1}{4}(2T_{\mathrm{s}}(1+E)+T_{\mathrm{o}}(2+21E))}T_{\mathrm{o}}T_{\mathrm{s}}^2$$

$$\zeta_2(E) = 2e^{\frac{23T_{\mathrm{o}}E}{4}+T_{\mathrm{s}}E}(T_{\mathrm{o}}-T_{\mathrm{s}})^2(3T_{\mathrm{o}}+T_{\mathrm{s}}) - 2e^{T_{\mathrm{o}}+\frac{19T_{\mathrm{o}}E}{4}+T_{\mathrm{s}}E}T_{\mathrm{s}}^2(3T_{\mathrm{o}}+T_{\mathrm{s}})$$

$$\zeta_3(E) = e^{T_{\mathrm{s}}+\frac{23T_{\mathrm{o}}E}{4}}T_{\mathrm{o}}\left(3T_{\mathrm{o}}^2 - 8T_{\mathrm{o}}T_{\mathrm{s}} - 3T_{\mathrm{s}}^2\right)$$

$$\eta_1(E) = -9e^{\frac{1}{6}(21T_{\mathrm{o}}+32T_{\mathrm{s}}+63T_{\mathrm{o}}E+34T_{\mathrm{s}}E)}T_{\mathrm{o}}(T_{\mathrm{o}}-T_{\mathrm{s}})^2(T_{\mathrm{o}}+T_{\mathrm{s}}) + 16e^{\frac{11}{2}T_{\mathrm{s}}(1+E)+2T_{\mathrm{o}}(2+5E)}T_{\mathrm{o}}T_{\mathrm{s}}^2(T_{\mathrm{o}}+T_{\mathrm{s}})$$

$$\eta_2(E) = -4e^{T_{\mathrm{s}}(7+5E)+\frac{1}{2}T_{\mathrm{o}}(5+21E)}T_{\mathrm{o}}T_{\mathrm{s}}^2(3T_{\mathrm{o}}+T_{\mathrm{s}}) - 2e^{\frac{1}{2}(T_{\mathrm{o}}+23T_{\mathrm{o}}E+2T_{\mathrm{s}}(5+6E))}T_{\mathrm{s}}^2\left(-3T_{\mathrm{o}}^2+2T_{\mathrm{o}}T_{\mathrm{s}}+T_{\mathrm{s}}^2\right)$$

$$\eta_3(E) = 2e^{\frac{7}{2}T_{\mathrm{o}}(1+3E)+2T_{\mathrm{s}}(2+3E)}(T_{\mathrm{o}}-T_{\mathrm{s}})^2\left(3T_{\mathrm{o}}^2+4T_{\mathrm{o}}T_{\mathrm{s}}+T_{\mathrm{s}}^2\right)$$

$$\eta_4(E) = 2e^{\frac{7}{2}T_{\mathrm{o}}(1+3E)+T_{\mathrm{s}}(5+6E)}(T_{\mathrm{o}}-T_{\mathrm{s}})^2\left(3T_{\mathrm{o}}^2+4T_{\mathrm{o}}T_{\mathrm{s}}+T_{\mathrm{s}}^2\right)$$

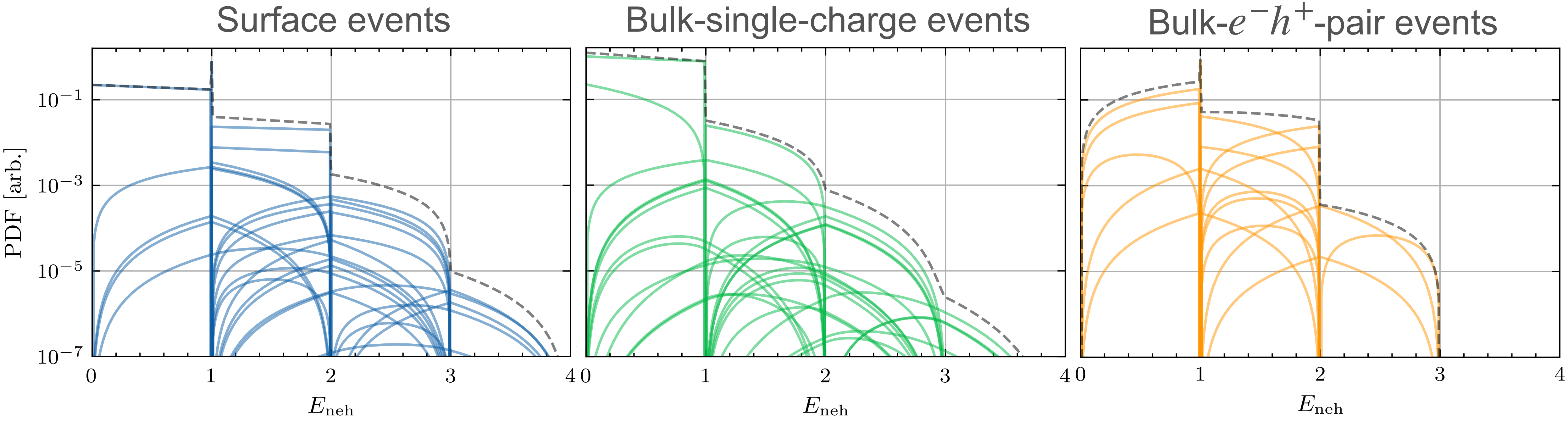
$$\eta_5(E) = -2e^{\frac{11T_{\mathrm{o}}}{2}+4T_{\mathrm{s}}+\frac{19T_{\mathrm{o}}E}{2}+6T_{\mathrm{s}}E}T_{\mathrm{s}}^2\left(3T_{\mathrm{o}}^2+4T_{\mathrm{o}}T_{\mathrm{s}}+T_{\mathrm{s}}^2\right)$$

$$\eta_6(E) = -e^{\frac{7}{2}T_{\mathrm{o}}(1+3E)+T_{\mathrm{s}}(2+7E)}T_{\mathrm{o}}\left(3T_{\mathrm{o}}^3+T_{\mathrm{o}}^2T_{\mathrm{s}}-3T_{\mathrm{o}}T_{\mathrm{s}}^2-T_{\mathrm{s}}^3\right)$$

$$\psi_1(E) = -2e^{T_{\mathrm{s}}+(T_{\mathrm{o}}+T_{\mathrm{s}})(-4+E)+T_{\mathrm{s}}E}T_{\mathrm{s}}^2 - 9e^{\frac{5}{3}T_{\mathrm{s}}(-1+E)}T_{\mathrm{o}}(T_{\mathrm{o}}+T_{\mathrm{s}})$$

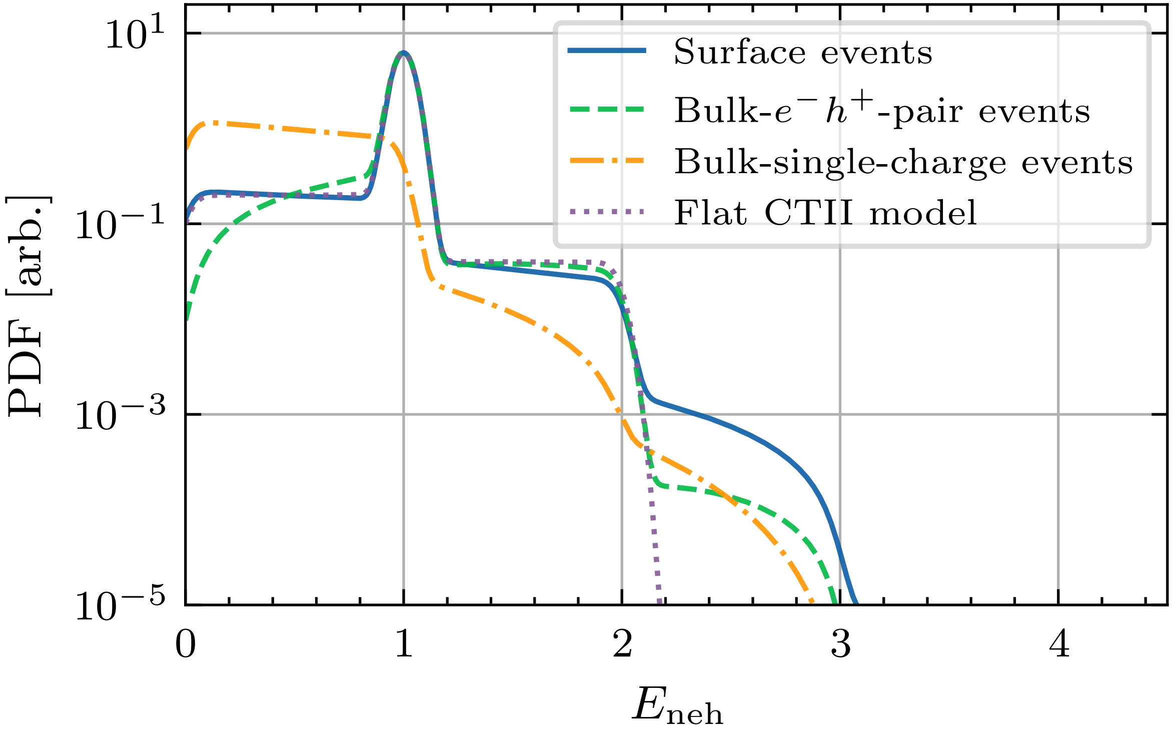
$$\psi_2(E) = e^{T_{\mathrm{s}}+T_{\mathrm{s}}E}T_{\mathrm{o}}(3T_{\mathrm{o}}+T_{\mathrm{s}}) + 2e^{T_{\mathrm{s}}(-3+2E)}\left(3T_{\mathrm{o}}^2+4T_{\mathrm{o}}T_{\mathrm{s}}+T_{\mathrm{s}}^2\right)$$

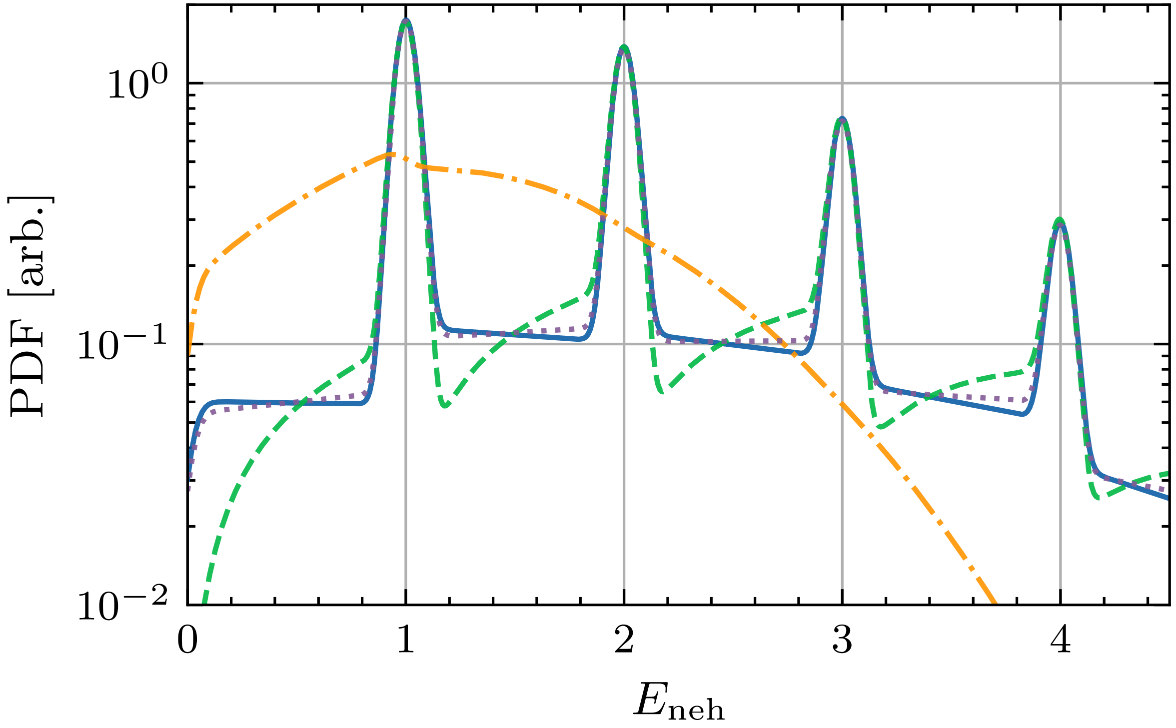
“Exponential” CTII model



Phys.Rev.D 109 (2024) 11, 112018

“Exponential” CTII model





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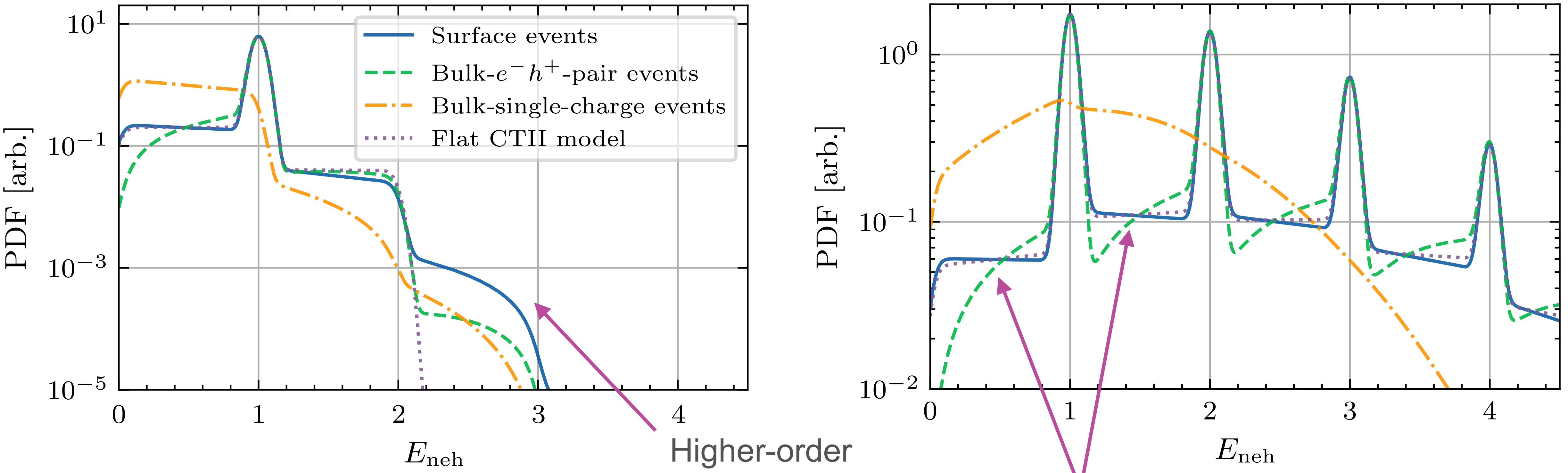
Flat CTII model (previous model): J Low Temp Phys 199, 598–605 (2020))

“Exponential” CTII model



Higher-order processes

Different shape for different event types

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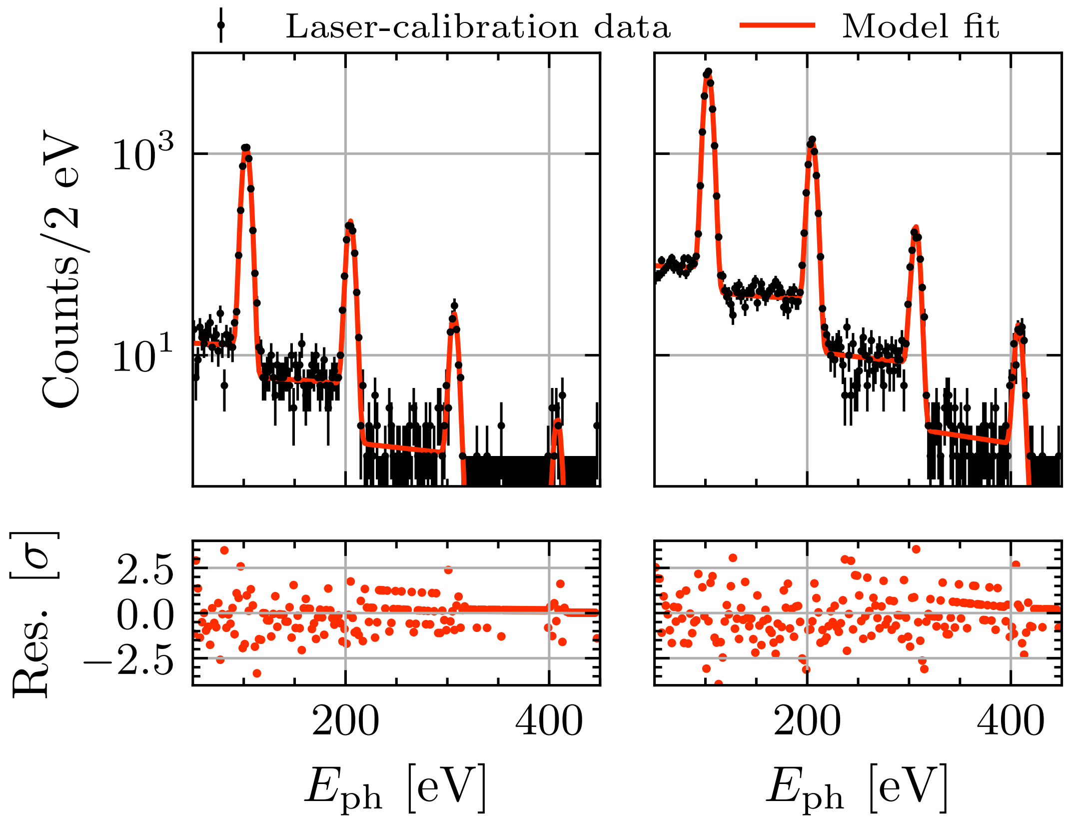
Flat CTII model (previous model): J Low Temp Phys 199, 598–605 (2020))

Surface events example: fit to laser data



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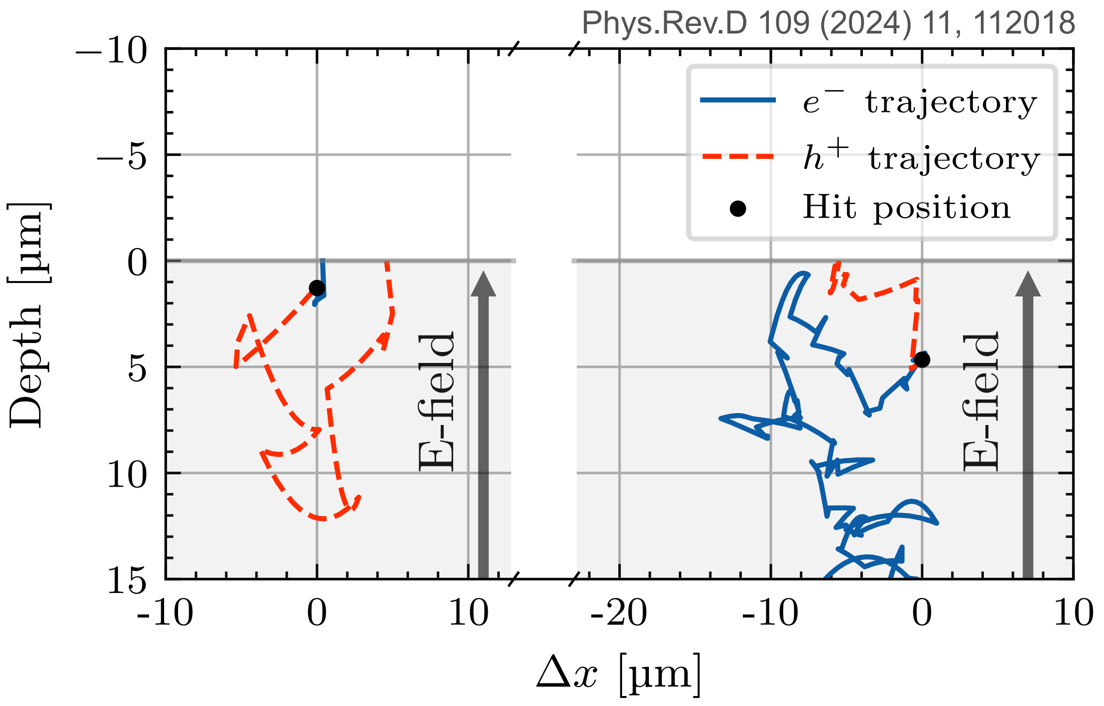
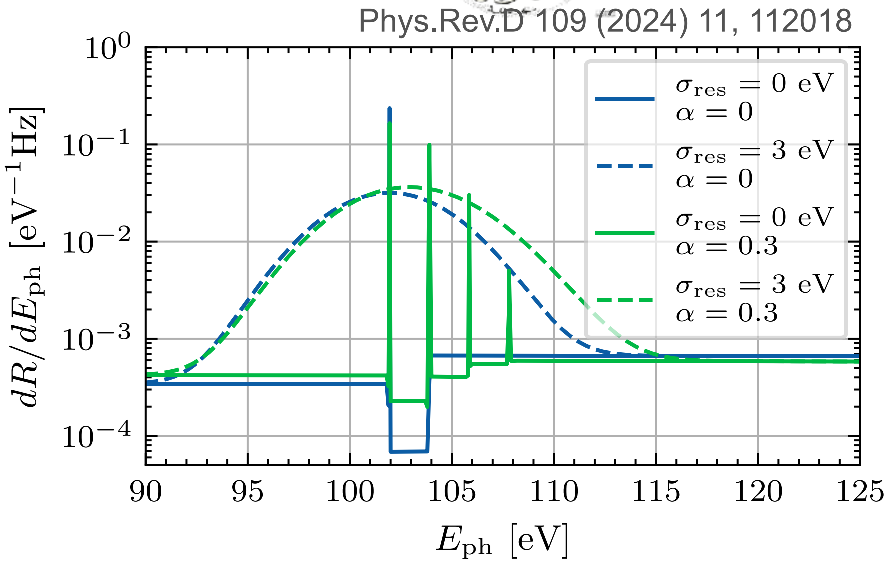
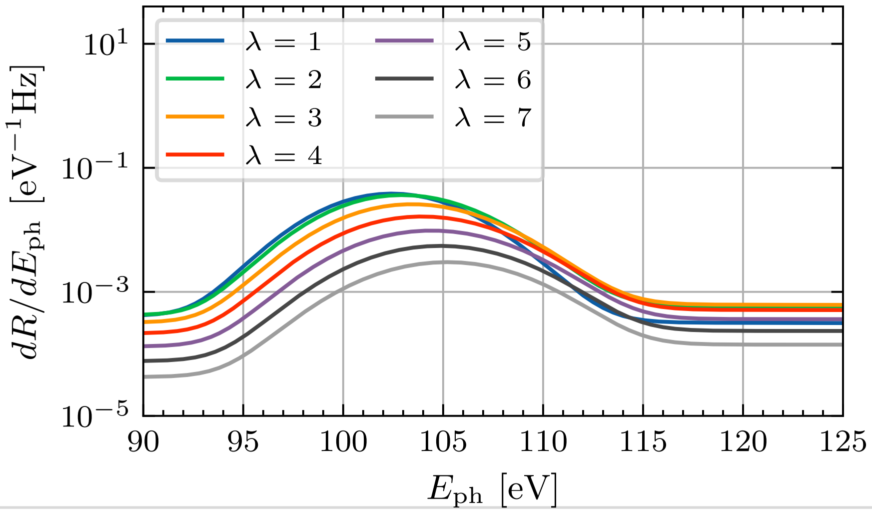
Left:	Right:
pCT = $11.6 \pm 0.6\,\%$	pCT = $12.1 \pm 0.3\,\%$
pII = $0.7 \pm 0.4\,\%$	pII = $0.9 \pm 0.2\,\%$
Poisson mean = 0.41 ± 0.01	Poisson mean = 0.475 ± 0.005
resolution = 3.30 ± 0.04 eV	resolution = 3.37 ± 0.02 eV

Non-ionizing energy deposition

One hypothesis: surface trapping





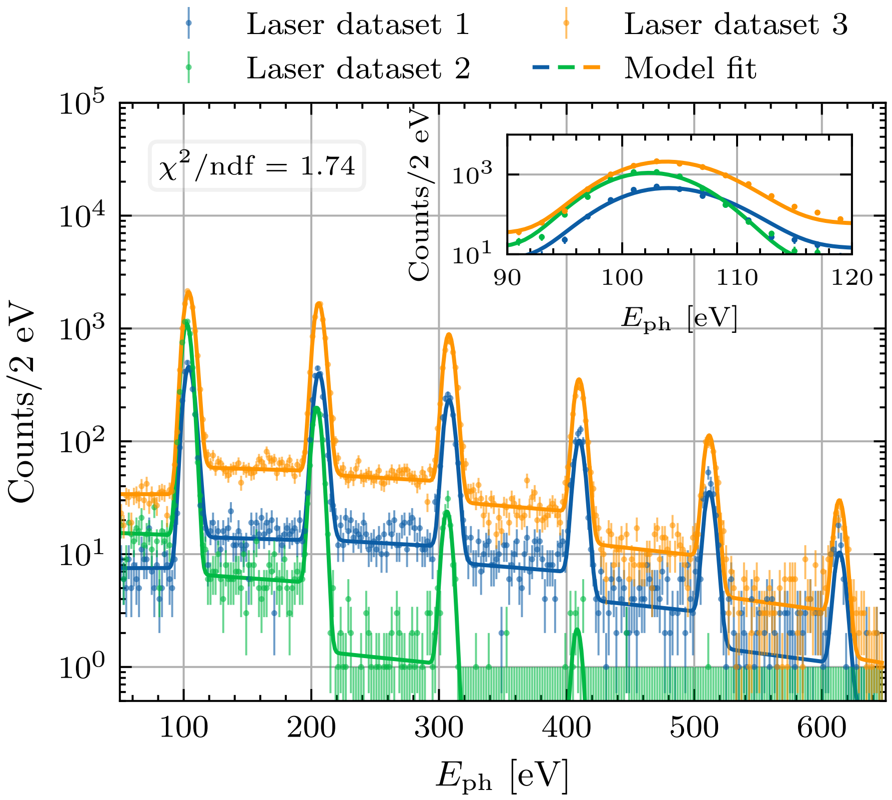


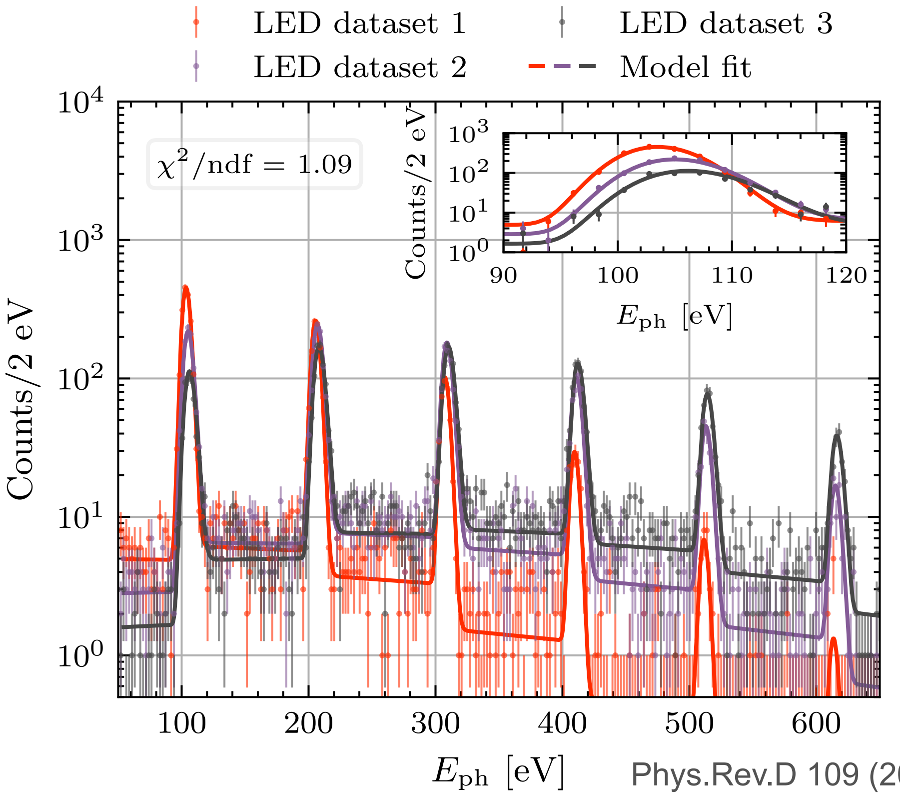
α = probability of surface trapping to occur

λ = Poisson mean of photons

Extended detector response fit

HVeV detectors made from same Si wafer





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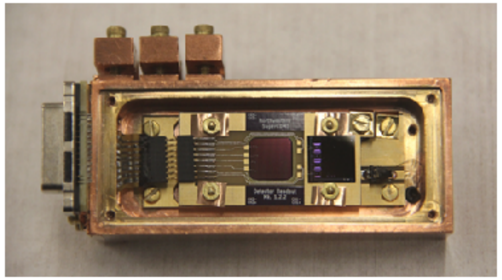
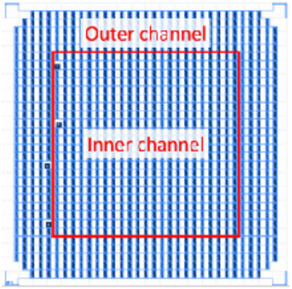
Phys.Rev.D 104 (2021) 03, 032010





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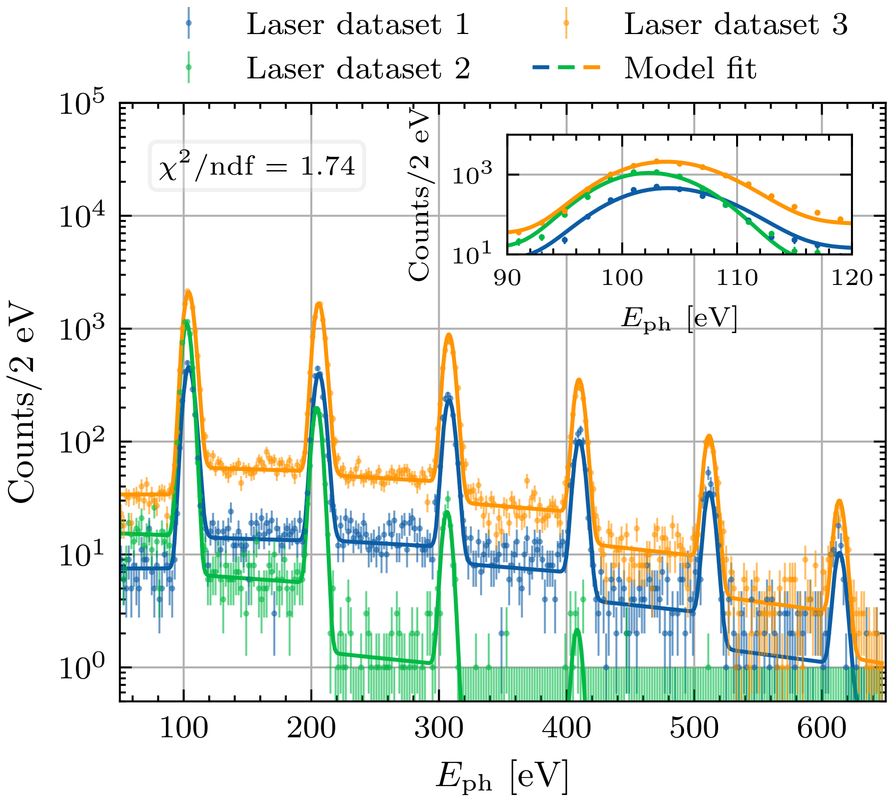
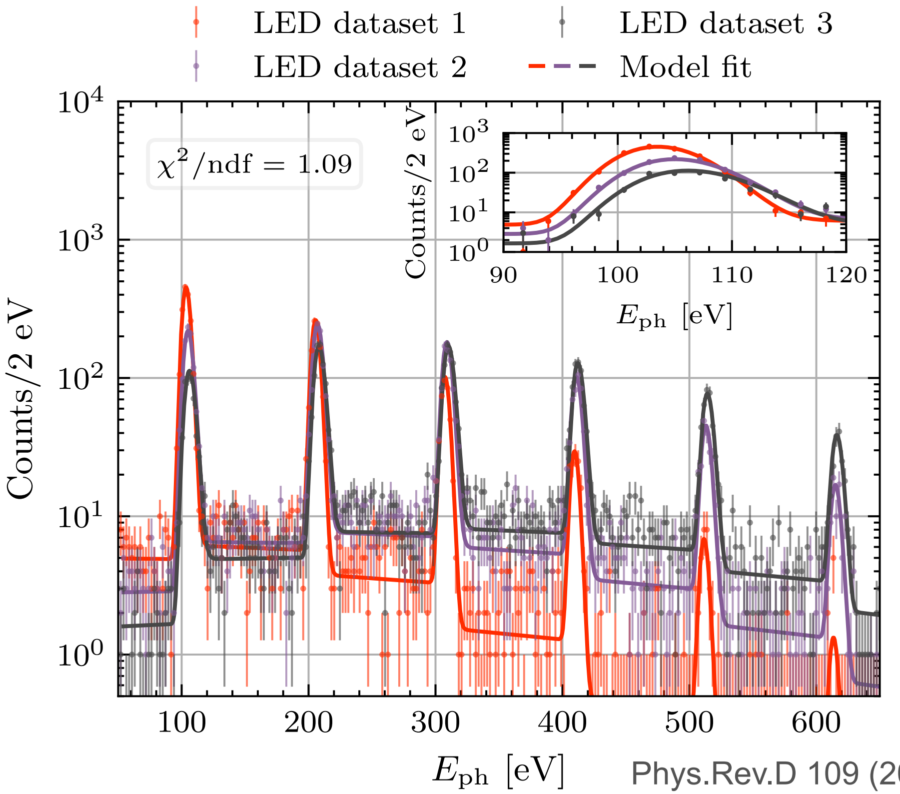


- initial charges are ***electrons***
- photons absorbed on surface ***with*** sensors



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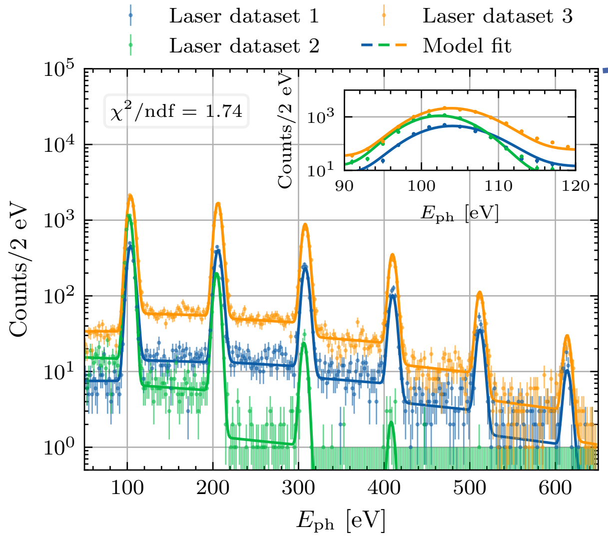
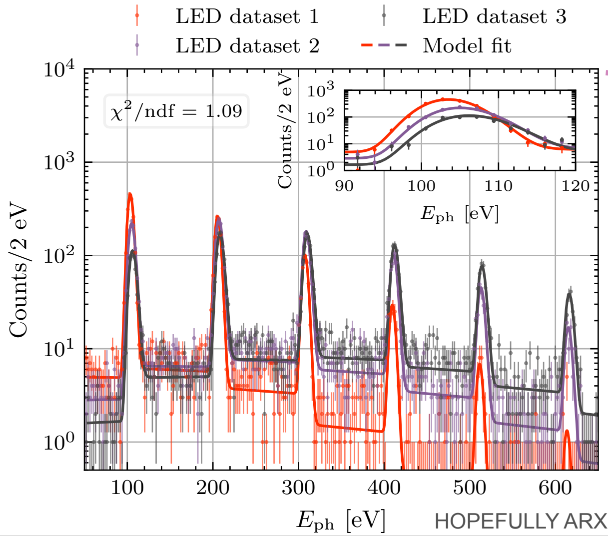
- initial charges are ***holes***
- photons absorbed on surface ***without*** sensors

Extended detector response fit





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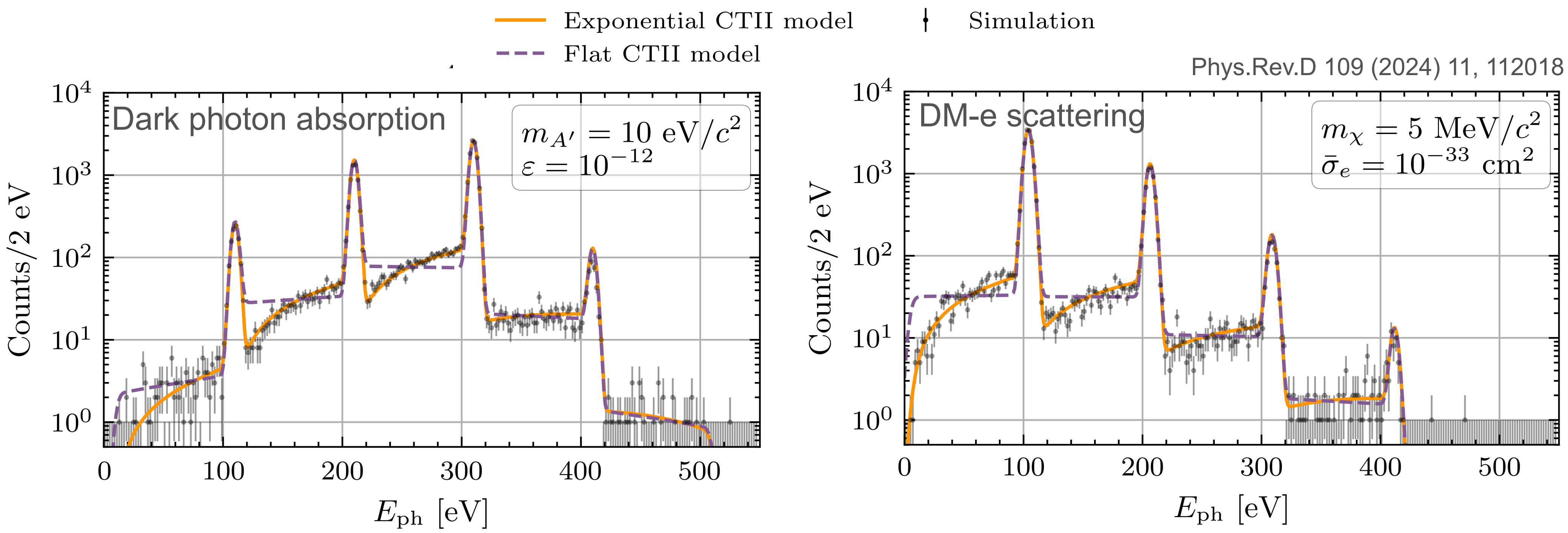
	Laser data (Ref. [8])	LED data (NEXUS)
λ_1	3.18 ± 0.04	2.2 ± 0.1
λ_2	0.66 ± 0.02	4.2 ± 0.2
λ_3	2.9[illegible] ± 0.03	5.7 ± 0.2
f_{CT} [%]	13.5 ± 0.2	11.5 ± 0.2
f_{II} [%]	0.4 ± 0.2	$0.0^{+0.3}_{-0.0}$
σ_{res} [eV]	3.41 ± 0.02	2.71 ± 0.06
α [%]	36.9 ± 0.7	41 ± 2
E_γ [eV]	–	2.02 ± 0.07
c_0 [μA]	–	$(1.7 \pm 0.2) \times 10^{-3}$
c_1 [μA/eV]	–	$(9.102 \pm 0.006) \times 10^{-4}$
c_2 [μA/eV^2]	–	$(-242 \pm 7) \times 10^{-10}$

- CT for electrons possibly higher than holes in these detectors
- α is high in both datasets - supports surface trapping hypothesis

Bulk events example: dark matter models

- Simulation of DM models with 6 g-days of exposure



Bulk events example: dark matter models

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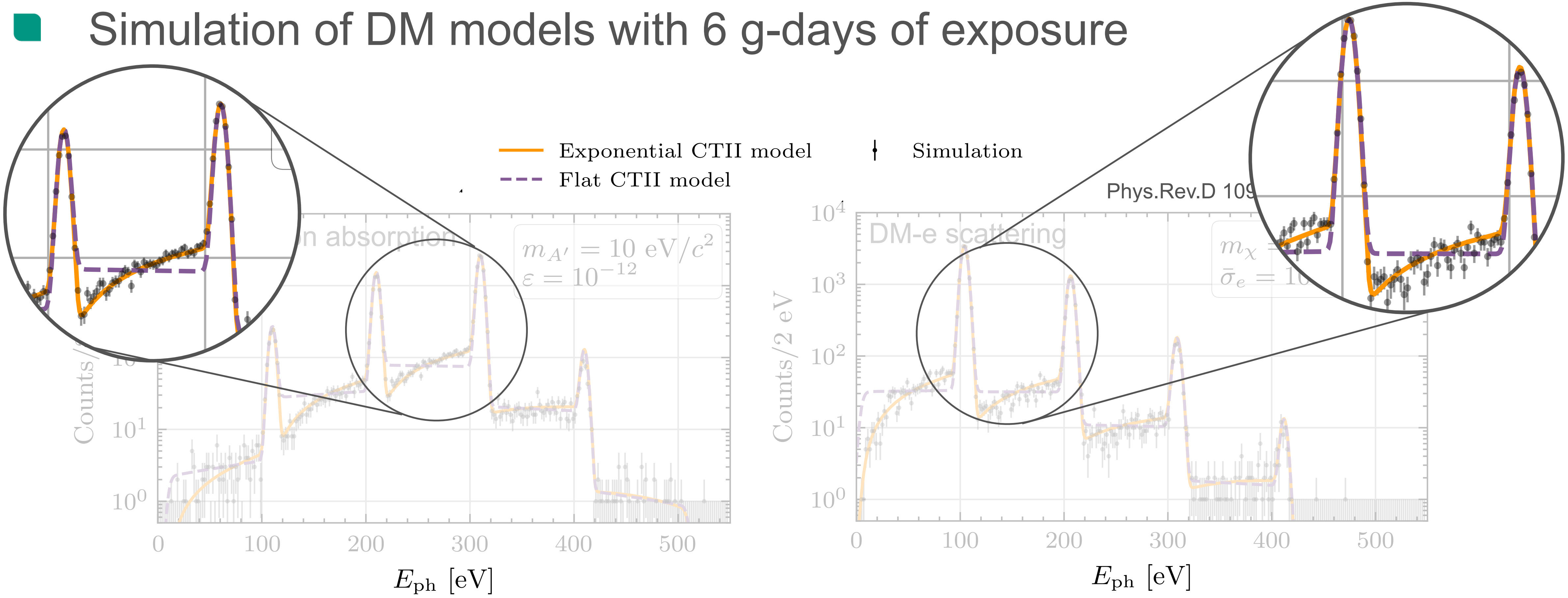
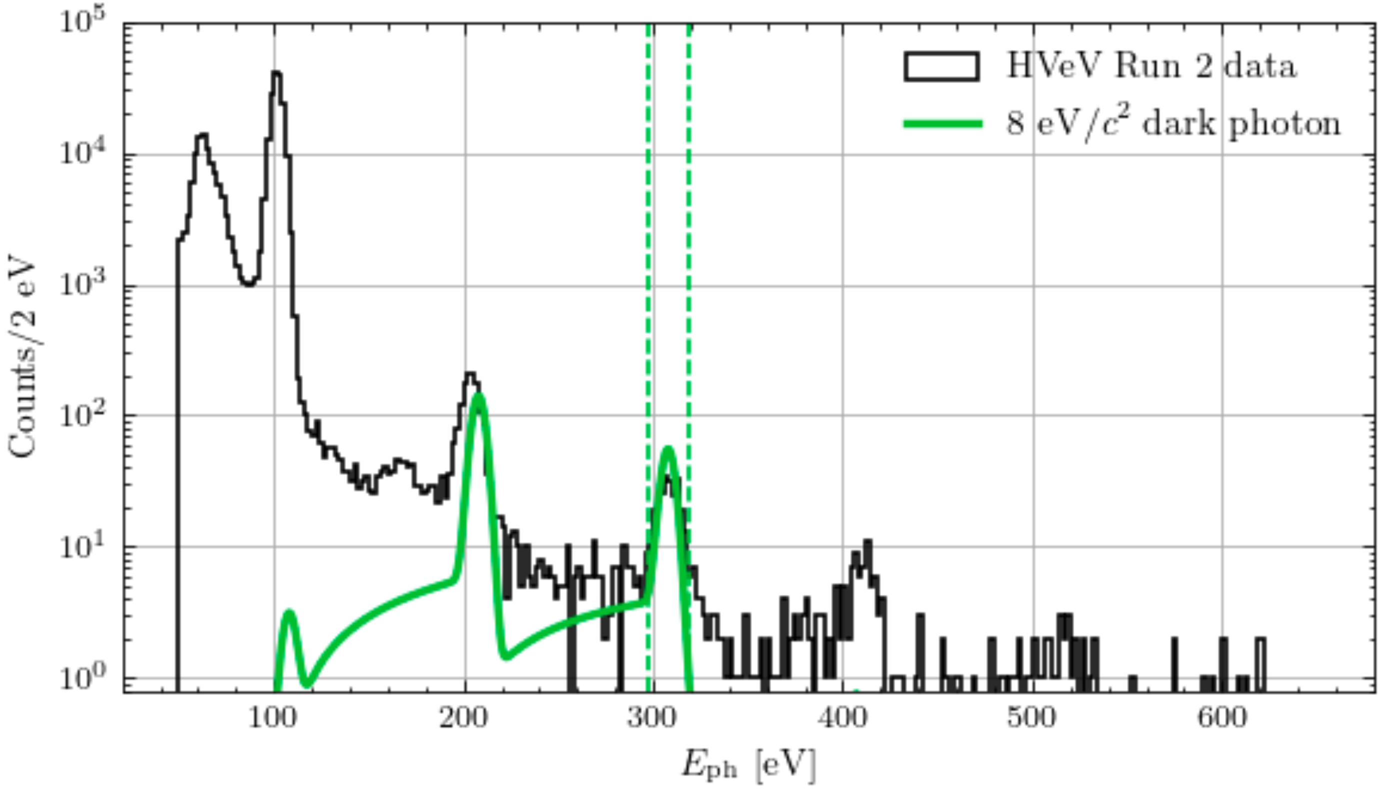


Gaining insights through detector response

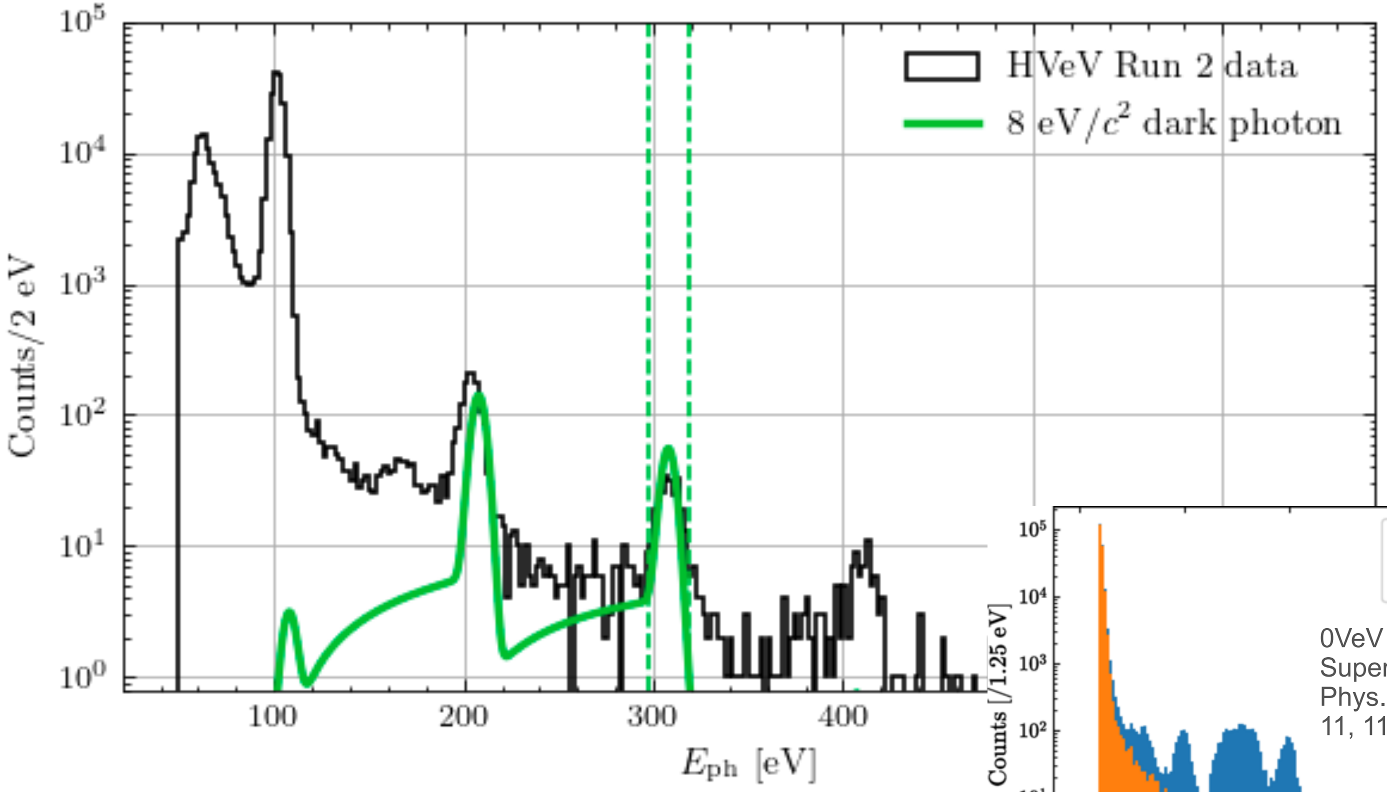
HVeV Run 2 data: SuperCDMS, Phys.Rev.D 102 (2020) 9, 091101

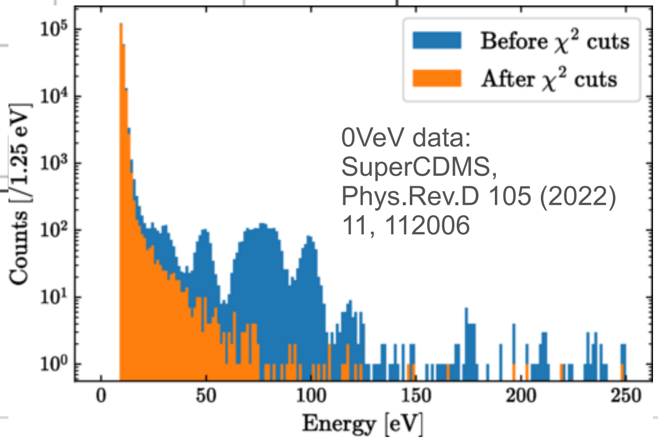


- Modelling detector response
  - Peak positions
  - Between-peak regions

Gaining insights through detector response

HVeV Run 2 data: SuperCDMS, Phys.Rev.D
102 (2020) 9, 091101





0VeV data:
SuperCDMS,
Phys.Rev.D 105 (2022)
11, 112006

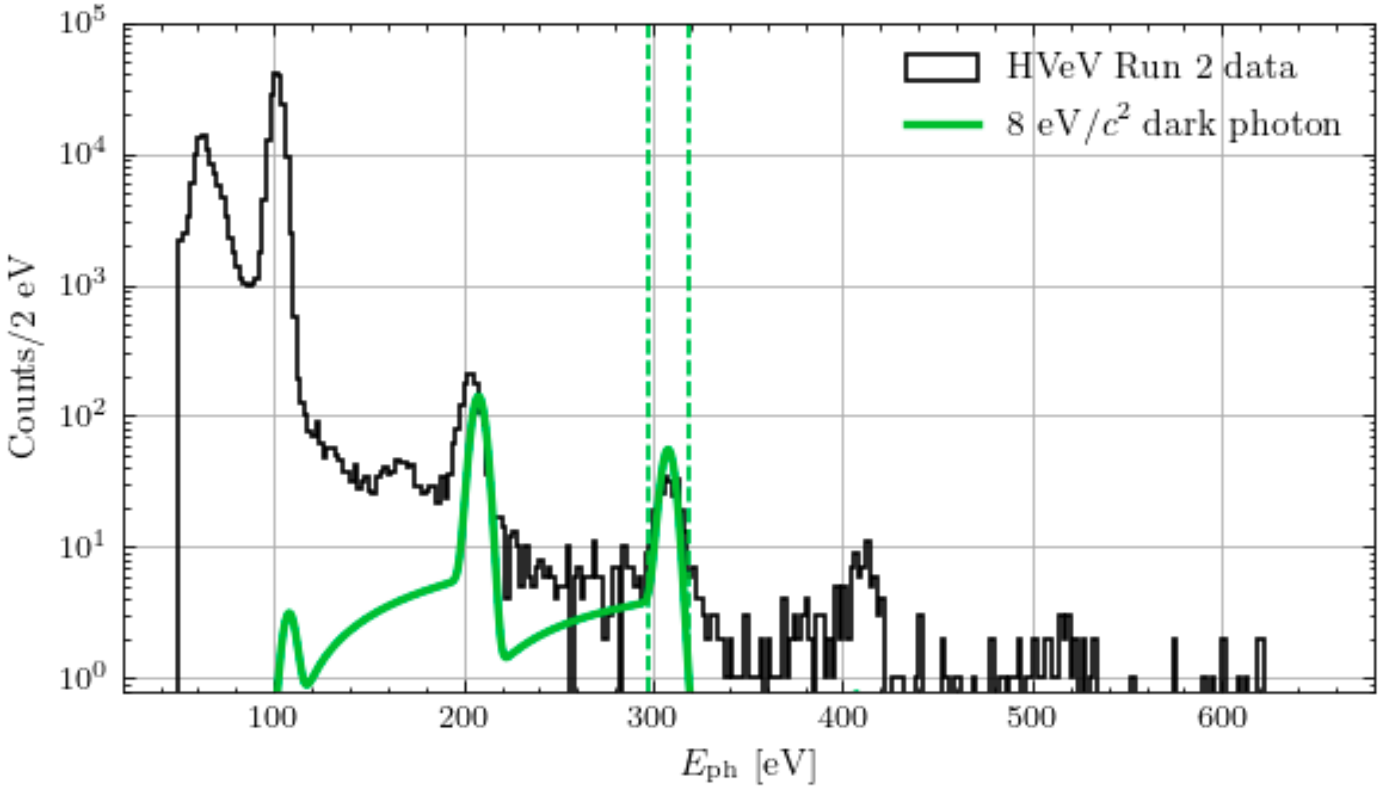
- Modelling detector response
  - Peak positions
  - Between-peak regions
- Understand backgrounds
  - Low-energy excess
  - Particle interactions (surface or bulk)

See upcoming HVeV results!

Poster 219: K. Kennard

Gaining insights through detector response

HVeV Run 2 data: SuperCDMS, Phys.Rev.D 102 (2020) 9, 091101



- Modelling detector response
  - Peak positions
  - Between-peak regions
- Understand backgrounds
  - Low-energy excess
  - Particle interactions (surface or bulk)
- Set stronger constraints on DM models

Summary and Outlook

- Our modelling can be used to improve:
  - measurements of detector response parameters
  - energy calibration (resolutions reaching ~1 eV)
  - ability to distinguish between sources of events
  - modelling of expected DM signals

- Motivates further measurements to better understand and investigate detector response effects

- These effects are present in other solid-state DM experiment (e.g. SENSEI, DAMIC-M)

SuperCDMS@IDM
Parallel 1, July 10: S. Dharani
Poster 109: S. Dharani
Poster 219: K. Kennard

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Recently published in PRD!
https://link.aps.org/doi/10.1103/PhysRevD.109.112018

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Improved modeling of detector response effects in phonon-based crystal detectors used for dark matter searches

M. J. Wilson, A. Zaytsev, B. von Krosigk, I. Alkhatib, M. Buchanan, R. Chen, M. D. Diamond, E. Figueroa-Feliciano, S. A. S. Harms, Z. Hong, K. T. Kennard, N. A. Kurinsky, R. Mahapatra, N. Mirabolfathi, V. Novati, M. Platt, R. Ren, A. Sattari, B. Schmidt, Y. Wang, S. Zatschler, E. Zhang, and A. Zuniga

Phys. Rev. D **109**, 112018 – Published 21 June 2024

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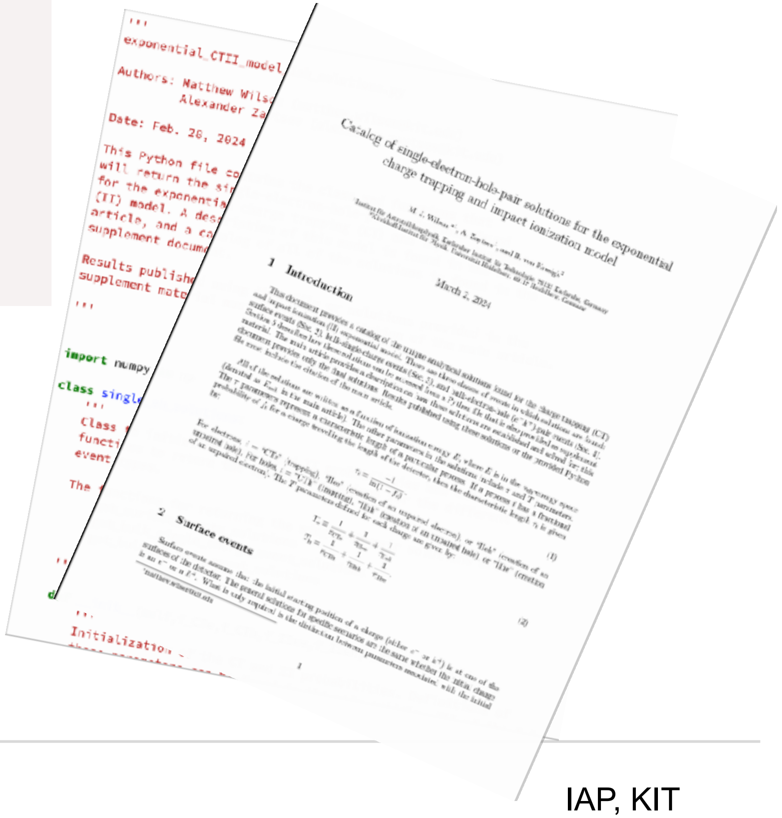
More

Article | References | No Citing Articles | Supplemental Material | PDF | HTML | Export Citation

Supplemental Material available:

- Catalog of analytic solutions
- Python script to load analytic solutions



Extra Slides

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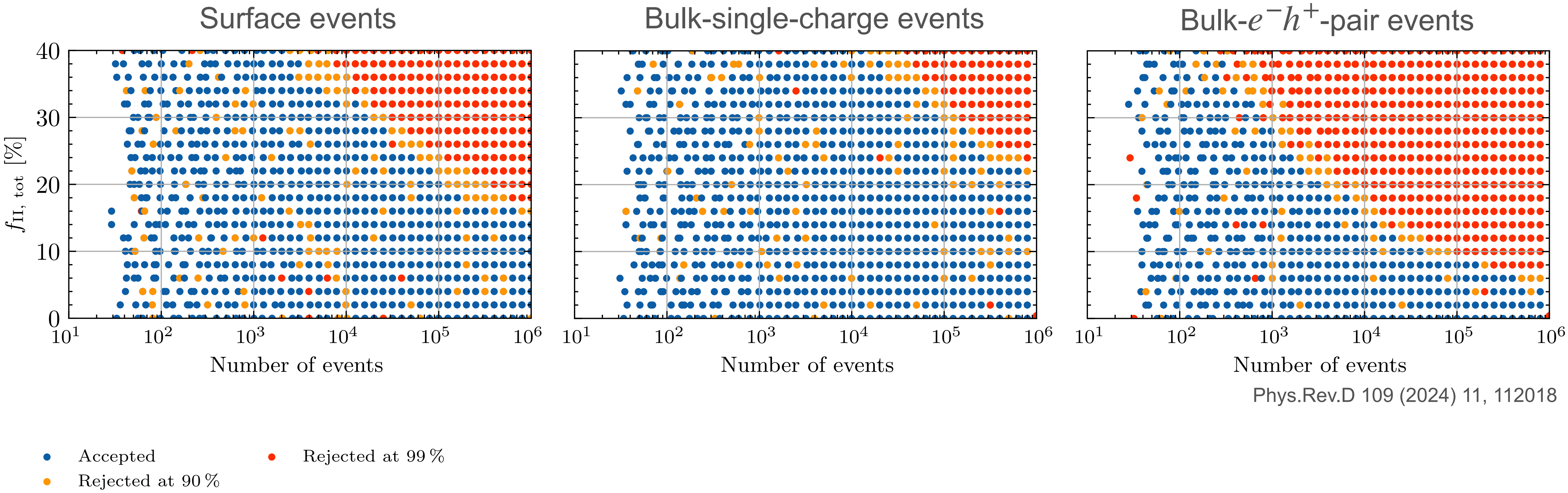
Limitations of Exponential CTII model



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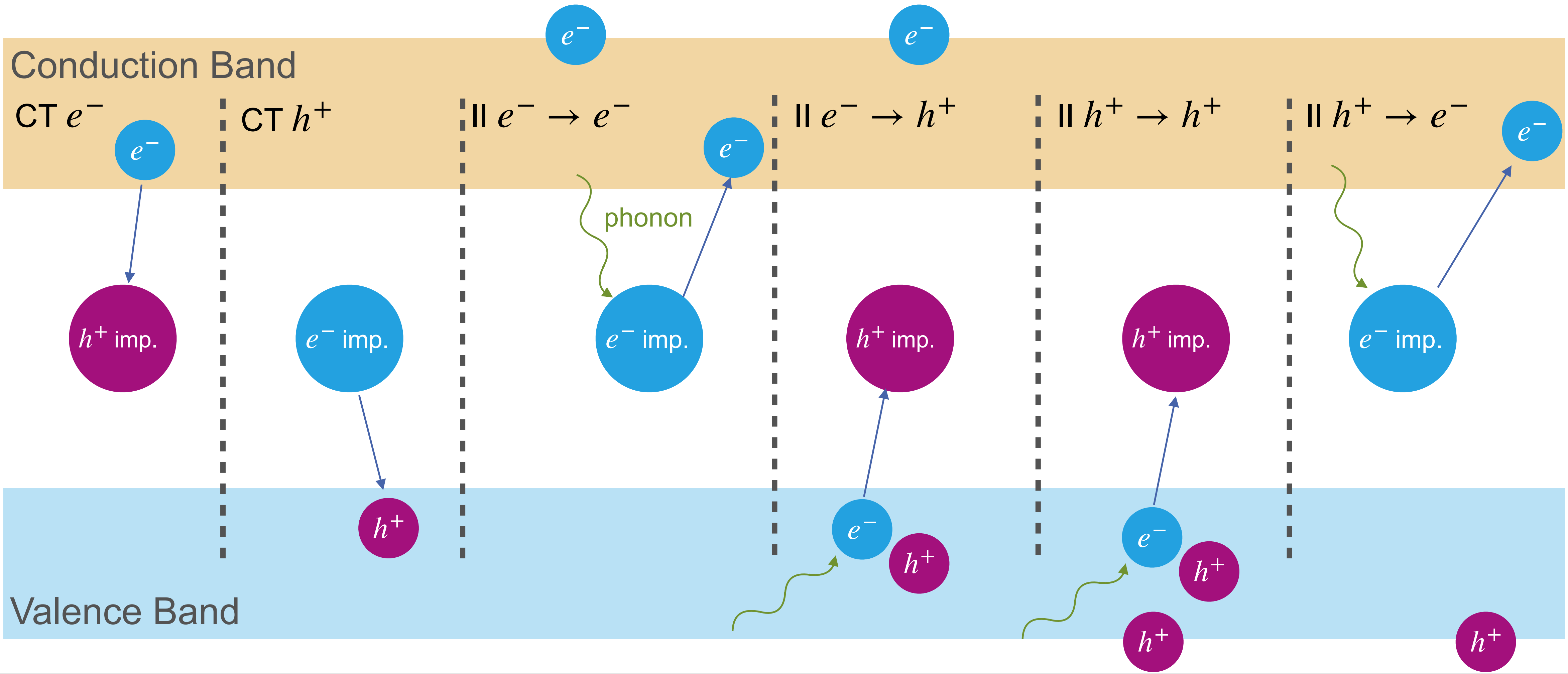
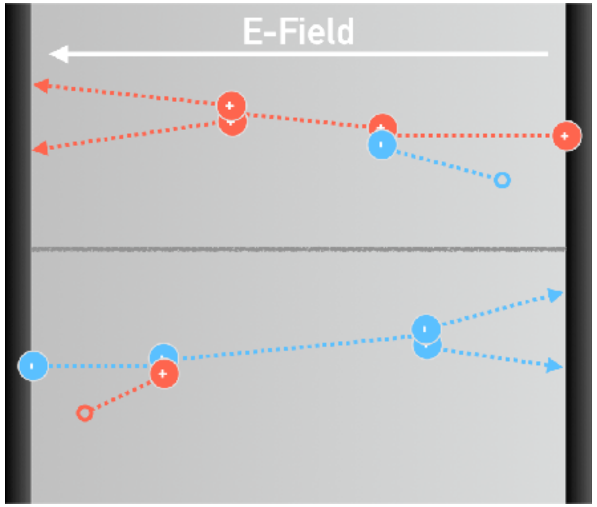
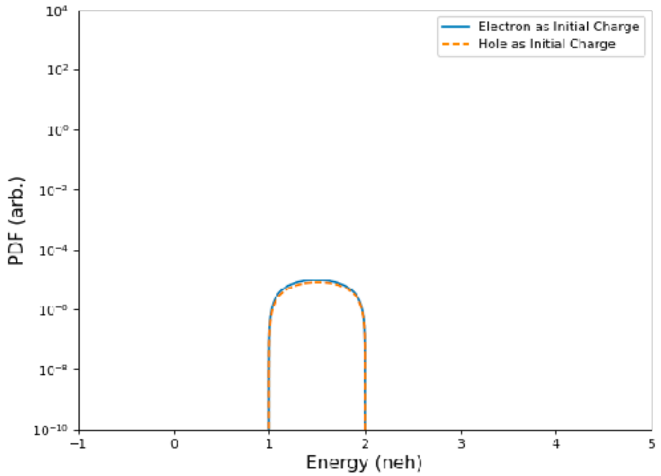
Possible CT/II mechanisms

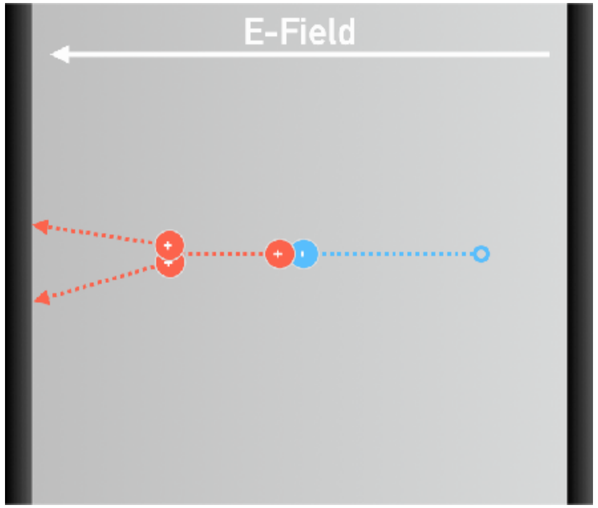


Examples of CT/II solutions

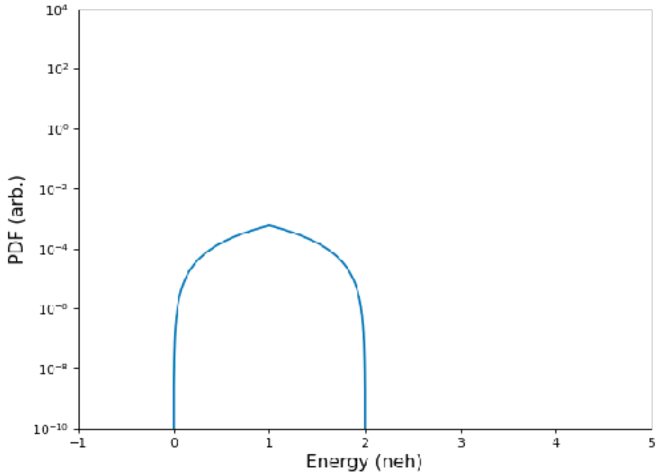


$$P(E) = \begin{cases} \dfrac{e^{-2T_s - T_o E}\left(e^{T_o + T_s} - e^{(T_o+T_s)E}\right)(-2+E)}{\tau_{t,o}(T_o+T_s)\tau_{i,so}\tau_{i,ss}} & 1 < E < 2 \\ 0 & \text{else}\,. \end{cases}$$

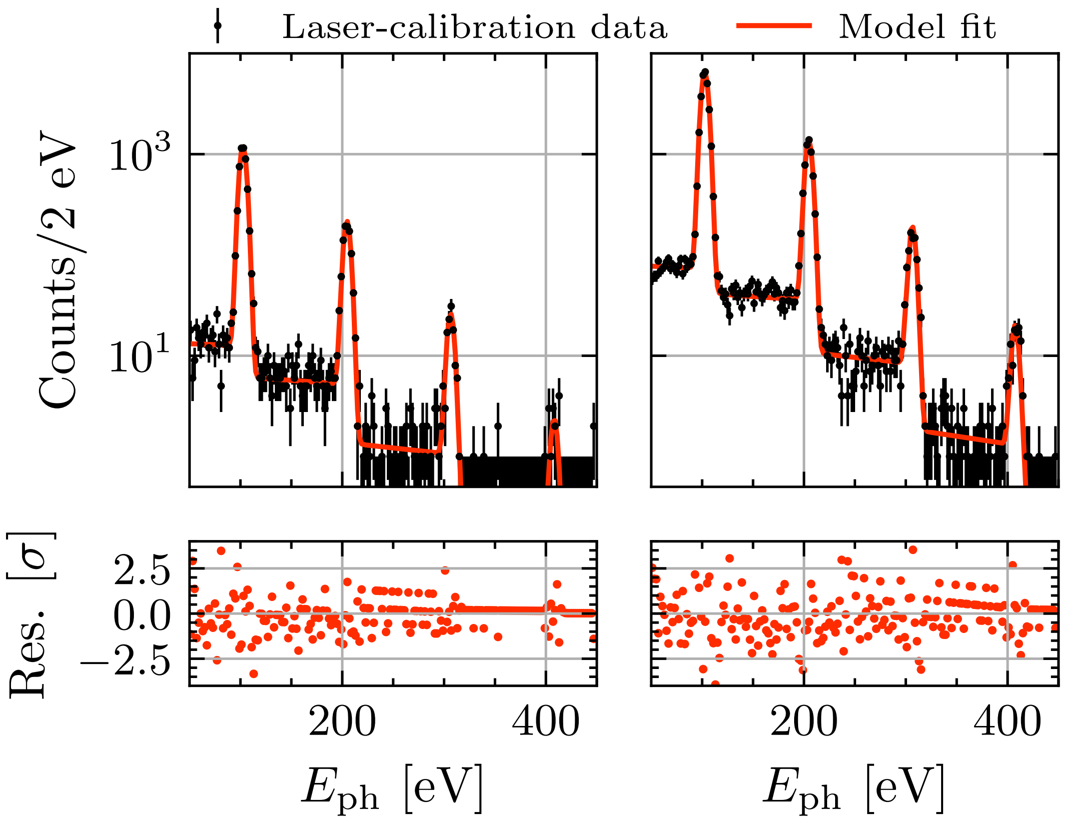




$$P(E) = \begin{cases} \dfrac{T_e - e^{-T_h E}T_e - T_h + e^{-T_e E}T_h}{2T_e^2\tau_{t,e}T_h\tau_{i,hh} - 2T_e\tau_{t,e}T_h^2\tau_{i,hh}} & 0 < E \leq 1 \\ \dfrac{T_e - e^{-2T_h + T_h E}T_e - T_h + e^{-2T_e + T_e E}T_h}{2T_e^2\tau_{t,e}T_h\tau_{i,hh} - 2T_e\tau_{t,e}T_h^2\tau_{i,hh}} & 1 < E < 2 \\ 0 & \text{else}\,. \end{cases}$$



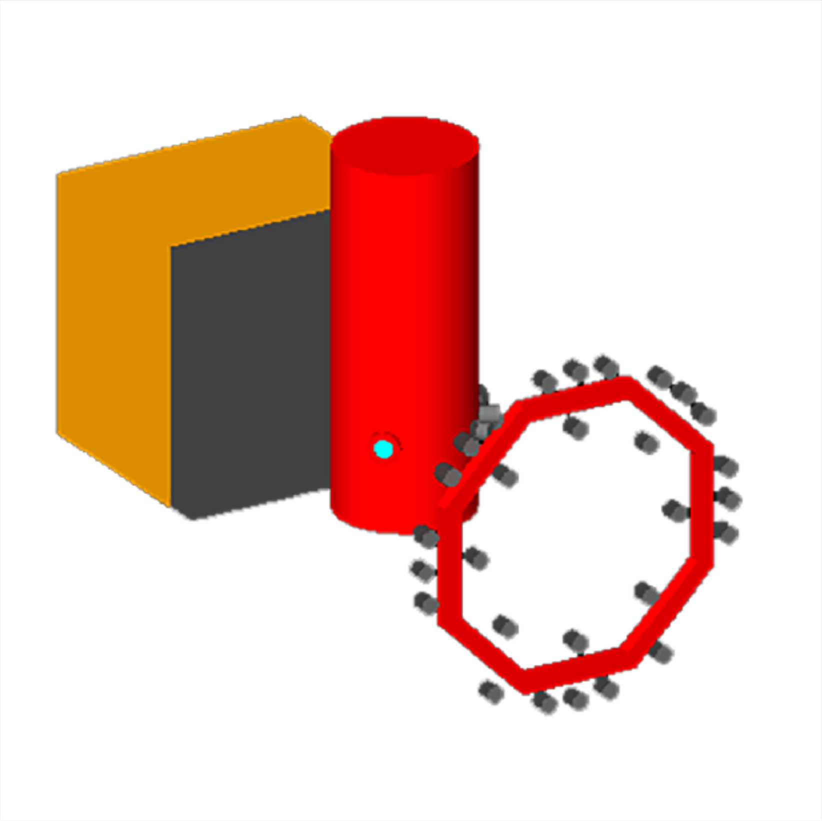
Flat vs Exponential CTII model

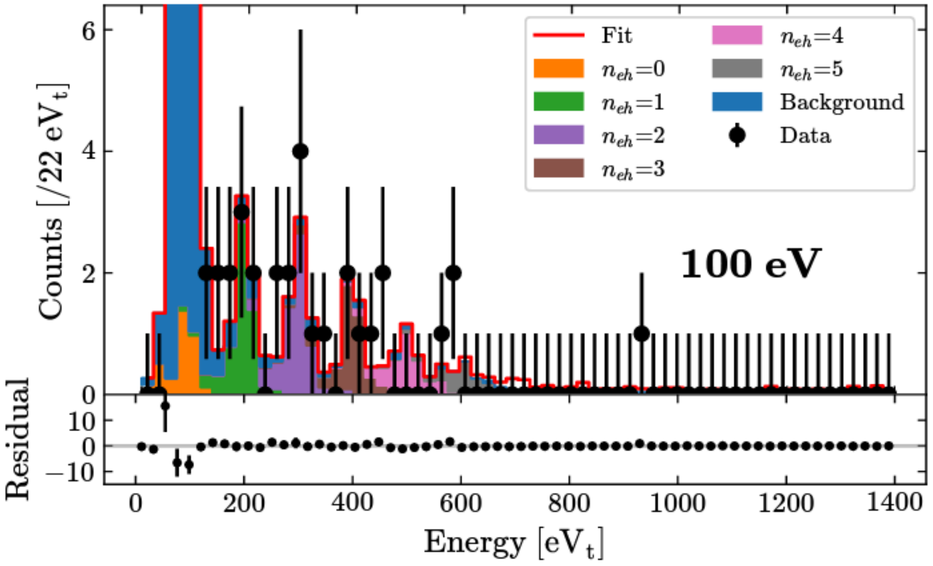


arXiv: 2403.01259

	Left:	Right:
Exponential CTII model	pCT = $11.6 \pm 0.6\,\%$ pII = $0.7 \pm 0.4\,\%$ Poisson mean = 0.41 ± 0.01 resolution = 3.30 ± 0.04 eV χ^2/ndf = 0.86	pCT = $12.1 \pm 0.3\,\%$ pII = $0.9 \pm 0.2\,\%$ Poisson mean = 0.475 ± 0.005 resolution = 3.37 ± 0.02 eV χ^2/ndf = 1.75
Flat CTII model	pCT = $11.5 \pm 0.6\,\%$ pII = $0.8 \pm 0.4\,\%$ Poisson mean = 0.41 ± 0.01 resolution = 3.24 ± 0.03 eV χ^2/ndf = 0.87	pCT = $12.0 \pm 0.3\,\%$ pII = $0.9 \pm 0.2\,\%$ Poisson mean = 0.476 ± 0.005 resolution = 3.31 ± 0.02 eV χ^2/ndf = 1.76

IMPACT analysis of nuclear ionization yield





Phys. Rev. Lett. 109 (2023) **131**, 091801